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An Analysis of Port State Control Performance for RORO Ships Using the Bayesian Network

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ABSTRACT

The number of maritime accidents involving roll-on/roll-off ships (RORO ships) resulting in casualties remains high. Currently, research on the maritime safety of RORO ships is relatively limited compared to that of other types of vessels. This study employs the Bayesian Network (BN) to analyze RORO ships recorded for deficiencies in the Memorandum of Understanding on Port State Control in the Asia-Pacific Region (Tokyo MOU) from 2015 to 2024, examining the most frequently logged deficiencies for RORO ships and their detention risks while exploring the key factors leading to the deficiencies or detentions. The analysis indicates that RORO passenger ships have a higher proportion of deficiencies related to personnel safety, while RORO cargo ships exhibit deficiencies not only in personnel safety but also in navigation safety and labour conditions. Additionally, RORO cargo ships have a higher detention rate than RORO passenger ones. The detention rate significantly increases when RORO cargo ships are recorded for structural conditions or other categories, and when RORO passenger ships are logged for other categories, International Safety Management (ISM), or safety of navigation. Furthermore, the detention rates increase significantly for RORO ships older than 30 years.

Keywords: RORO cargo ships, RORO passenger ships, Bayesian Network, Port State Control.

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1 INTRODUCTION

Maritime safety has always been an important issue. Navigation safety has consistently been one of the top priorities for the International Maritime Organization (IMO), which continuously formulates and updates regulations and conventions related to maritime safety. To ensure that vessels comply with international requirements, contracting governments must conduct inspections of foreign vessels through Port State Control (PSC) to ensure compliance with the minimum standards of international conventions, regional agreements, and domestic regulations. This mechanism is an effective means of enhancing the safety of vessels, personnel, and cargo.

The majority of maritime safety studies focuses on ship types with a higher number of accidents, such as bulk carriers, general cargo ships, containers, and oil/chemical tankers. There is, however, relatively less research concerning roll-on/roll-off ships (RORO ships). Such ships offer flexibility in carrying passengers and cargo and better integration with other transport modes; in addition, they enhance the efficiency of boarding and disembarking (European Maritime Safety Agency [EMSA], 2018). However, the design of RORO ships introduces specific risks during operations. According to the European Maritime Safety Agency's (EMSA) 2021 Annual Overview of Marine Casualties and Incidents, casualties in passenger ship incidents are equally split between ships carrying only passengers and ships carrying both passengers and RORO cargo (EMSA, 2022). Furthermore, the report indicates that between 2014 and 2020, RORO cargo ships (RORO cargo) are one of the four ship types where the occurrence of accidents exceeded their historical average. During this period, the annual number of accidents for this ship type consistently remained between 200 and 300, showing no downward trend. In Table 5 of the Annual Report on Port State Control in the Asia-Pacific Region 2023, the detention rate for RORO cargo ships during PSC inspections was 13.64%, ranking as the second highest among all ship types (Tokyo MOU, 2023). Accordingly, there is a need to scrutinize RORO PSC performance.

This study evaluates RORO ship safety using the Bayesian Network (BN) to analyze the deficiency items most frequently cited and their detention risk during PSC inspections. This study investigates the key elements leading to these deficiencies with the aim of enhancing maritime safety. The outcomes generated can serve as a valuable reference for maritime authorities, shipowners, cargo owners, and other stakeholders.

2 LITERATURE REVIEW

2.1 BN-Based PSC Studies

The BN model is a commonly used method for maritime safety analysis. This method allows for probabilistic inference through the causal relationships between its nodes. The BN structure provides a vivid picture illustrating the mutual influence of each parameter and enables the overall effects to be appreciated given the status of each node. Furthermore, the technique is capable of conducting reverse inferences to determine the key causes and the most unfavorable combination of node states leading to a particular ship accident, deficiency, or detention. It also has the strength of combining qualitative and quantitative data, allowing for the integration of expert and academic opinions with objective data (Yang et al., 2021). Therefore, models based on the BN are able to become more relevant to practical applications. The following works are the PSC studies that are based on the BN mechanism.

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Hänninen and Kujala (2014) established a Bayesian model using the Necessary Path Condition Algorithm (NPC Algorithm) and the Hill-Climbing Algorithm to analyze the relationships between different types of deficiencies recorded from PSC inspections and the correlation between such deficiency types and ship marine casualties. Yang et al. (2018) examined bulk carrier inspection data from seven major European countries within the Paris Memorandum of Understanding (Paris MOU) from 2005 to 2008 with the use of the Tree Augmented Naive Bayes (TAN) method to analyze risk factors influencing PSC inspections and to predict the probability of ship detention. Fan, Zhang, et al. (2019) constructed a BN structure to investigate the effect of PSC inspections on ship accidents and the ship's safety level in the subsequent inspection, considering the ship's inherent attributes and the time interval between inspections. The results showed that the safety level of the initial inspection significantly influences both the time interval and the safety level of the second inspection. The study suggested that selecting ships with a medium inspection time interval for inspection could effectively enhance ship safety quality. Yang et al. (2021) proposed a methodology for ship detention risk control by incorporating a BN into the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method and dynamically evaluated the effectiveness of each strategy in reducing the detention rate. Fan, Wang, and Yin (2019) learned the BN structure by virtue of the Greedy Thick Thinning (GTT) algorithm and evaluated the impact of various factors on the ship's risk level and accident consequences using K-fold cross validation, the log-likelihood function (LL), and the Akaike Information Criterion (AIC). The study results indicated that ship age, ship type, and the PSC inspection level have the most significant impact on the ship risk level.

2.2 PSC Studies Considering RORO Ships

While fewer PSC studies specifically focus on RORO vessels, a number of studies analyze PSC inspections across multiple ship types, with some of these studies spending efforts on RORO vessels. Şanlıer (2020) analyzed ship deficiencies and detention records collected from Black Sea Memorandum of Understanding (BS MOU) PSC inspections from 2012 to 2017. The study reveals that the main factor for detention was ship age and the effects of ship type, flag state, Recognized Organization (RO), and Classification Society (CS) were significant. Cariou et al. (2008), using data from the Swedish Maritime Administration (1996-2001), analyzed the extent to which ship characteristics influence the time interval between two PSC inspections and the number of deficiencies detected during a PSC inspection. The research indicated that ship age, ship type, and flag state appear to be important predictors. This study pointed out that passenger ships and RORO passenger ships were inspected more frequently and also appeared to exhibit more deficiencies compared to other ship types. Cariou et al. (2007) made use of PSC reports from the Swedish Maritime Administration from 1996 to 2001 to scrutinize the factors affecting ship deficiencies and concluded that ship age, ship type, and flag were the three determining factors. Furthermore, this study noted that passenger ships and RORO passenger ones had more deficiencies, most of which occurred on RORO passenger vessels around 22 years of age. Kim et al. (2014), by analyzing PSC inspection data from the Tokyo MOU and the Korean Ministry of Oceans and Fisheries, examined the deficiency rate and detention rate of ships. A decreasing trend was found in both the deficiency and detention rates. However, ships over 30 years old, flags of convenience (FOC) ships, RORO vessels and general cargo ships, and vessels under 1,000 gross tons consistently had high deficiency and detention rates.

3 METHODOLOGY

This study first conducted BN analysis to examine the causal relationships and influences among variables, assessing the factors contributing to deficiencies and detentions of RORO vessels. The model structure was initially established by referencing node associations from relevant literatures and subsequently refined based on feedbacks from experts. By constructing a BN evaluation model for RORO vessel PSC, the marginal probability mechanism of the Bayesian inference was utilized to derive the probabilities of ship detention and each deficiency category. Furthermore, the posterior probability mechanism could be utilized to identify the key elements for deficiencies and detention, and scenario analysis could be performed for specific vessels to determine their probabilities of detention and each deficiency type.

3.1 Data Collection

This study collected the deficiencies recorded for RORO cargo and RORO passenger vessels cited within the Tokyo MOU from 2015 to 2024. The data includes 8 items, namely, Defective Item, Detention Status, Number of Deficiencies, Inspection Type, Performance of Recognized Organization (RO), Gross Tonnage, Ship Age, and Ship Risk Profile (SRP). Between 2015 and 2024, a total of 239 individual RORO cargo ships were inspected, resulting in 1,115 inspections and 5,917 deficiencies. In total, 83 individual RORO passenger vessels were inspected, leading to 4,783 deficiencies in 1,359 inspections. Table 1 and Table 2 contain the nodes and states for RORO cargo and RORO passenger ships, respectively.

According to the Annual Report on Port State Control in the Asia-Pacific Region, Performance of RO is divided into three categories, namely, Low, Medium, and High (Tokyo MOU 2023). In addition, NA will be used as a note for ROs outside the calculation scope in this study.

There are 17 ship deficiency sections according to Tokyo MOU deficiency codes. These include Certificate & Documentation, Structural Conditions, Water/Weathertight Condition, Emergency Systems, Radio Communications, Cargo Operations Including Equipment, Fire Safety, Alarms, Working and Living Conditions, Safety of Navigation, Life Saving Appliances, Dangerous Goods, Propulsion and Auxiliary Machinery, Pollution Prevention, International Safety Management (ISM), Labour Conditions, and Others.

To ensure effective model analysis, the constructed model will be adjusted based on the data characteristics of the node states. That is, node states with smaller sample sizes will be merged. Accordingly, in the BN model for RORO cargo ships, the following categories were combined, namely, Cargo Operations Including Equipment, Alarms, Dangerous Goods, and Others. In the BN model constructed for RORO passenger ships, on the other hand, the categories of Radio Communications, Alarms, Dangerous Goods, and Others were merged.

Considering that the total number of deficiencies recorded for most vessels is concentrated below five, the counts were categorized as 1-3 times, 4-5 times, followed by 6-10 times, 11-15 times, 16-20 times, and over 20 times. Inspection Type is divided into Initial and Follow-up inspections, a classification which includes remote initial inspections and remote follow-up inspections. Detention is divided into two states, Yes and No. Ship Age and Gross Tonnage are segmented based on the data distribution of the two vessel types, merging categories with smaller counts and further subdividing categories with denser distribution. For example, RORO cargo vessels aged 30 and over are further divided into 31-35 years and over 35 years. The Ship Risk Profile (SRP) is categorized into High Risk Ship, Standard Risk Ship, Low Risk Ship, and None (unrecorded).

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Table 1. Nodes and states of RORO cargo ships.

Node	States						
Nb of Deficiencies	1-3	4-5	6-10	11-15	16-20	Over 20	-
Defective Item	Fire Safety	Safety of Navigation	Labour Conditions	Certificate & Documentation	Life Saving Appliances	Propulsion and Auxiliary Machinery	Water/ Weathertight Conditions
	Emergency Systems	Pollution Prevention	ISM	Structural Conditions	Radio Communications	Working and Living Conditions	Others (Others/DG/ Alarms /Cargo operations)
Inspection Type	Follow-up	Initial	-	-	-	-	-
Detention	No	Yes	-	-	-	-	-
Performance of RO	High	Medium	NA	-	-	-	-
Ship Age	0-10 years	11-15 years	16-20 years	21-25 years	26-30 years	31-35 years	Over 35 years
Gross Tonnage	0-5,000	5,001-10,000	10,001-15,000	15,001-20,000	Over 20,000	-	-
Ship Risk Profile	High Risk Ship	Standard Risk Ship	Low Risk Ship	None	-	-	-

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Table 2. Nodes and states of RORO passenger ships.

Node	States						
Defective Item	Cargo Operations Including Equipment	Certificate & Documentation	Emergency Systems	Fire Safety	ISM	Labour Conditions	Life Saving Appliances
	Pollution Prevention	Propulsion and Auxiliary Machinery	Safety of Navigation	Structural Conditions	Water/ Weathertight Conditions	Working and Living Conditions	Others (Radio Communications/ Alarms/DG)
Nb of Deficiencies	1-3	4-5	6-10	11-15	16-20	Over 20	-
Inspection Type	Follow-up	Initial	-	-	-	-	-
Detention	No	Yes	-	-	-	-	-
Performance of RO	High	Medium	NA	-	-	-	-
Ship Age	0-10 years	11-15 years	16-20 years	21-25 years	26-30 years	Over 30 years	-
Gross Tonnage	0-10,000	10,001-15,000	15,001-20,000	20,001-25,000	25,001-30,000	30,001-35,000	Over 35,000
Ship Risk Profile	High Risk Ship	Standard Risk Ship	Low Risk Ship	None	-	-	-

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3.2 Bayesian Network Construction

Based on the deficiencies recorded for RORO ships from the Tokyo MOU database from 2015 to 2024, this study constructed two PSC Bayesian models for RORO cargo vessels and RORO passenger ones, respectively. The Bayesian models comprise eight nodes. The associations between nodes were established based on the expert opinions and relevant international literatures (Dinis et al., 2020; Fan, Zhang, et al., 2019; Hänninen & Kujala, 2014; Jiang et al., 2023; Wang et al., 2021; Yang et al., 2018), and were finalized through expert revision.

Bayesian inference is a method based on Bayes' Theorem that uses probability as an index to represent the magnitudes. It is such an approach that is based on an event's prior belief and continually updates the model by obtaining new evidence. The prior belief can be historical data or the subjective belief of experts and scholars, which forms the prior probability (Yang et al., 2018). Conditional probability, joint probability, and marginal probability are subsequently developed based on the causal relationships between the nodes. By virtue of Bayesian inference, the posterior probability is able to be acquired. A BN diagram is a Directed Acyclic Graph (DAG), where random variables are represented by node. The dependencies between such nodes are represented by arcs, which point from the parent node (cause) to the child node (effect).

Suppose y_j represents a parent node which is described by the state n and there are J parent nodes depicted by N states. $P(y_{jn})$ denotes the prior probability of the parent node y_j under the state n. Also, let x_i denote a child node x under the state i and is influenced by the J parent nodes. The marginal probability of x_i can be acquired using Equation (1).

$$P(x_i) = \sum_{j=1}^{J} \sum_{n=1}^{N} P(x_i|y_{jn})P(y_{jn}) \tag{1}$$

$P(x_i)$ is the marginal probability of the child node x under the ith state considering each state of all parent nodes. $P(x_i \mid y_{jn})$ represents the conditional probability of x_i subject to the parent node y_j under the state n.

The posterior probability of the parent node y_j under the state n given the occurrence of x_i , can be obtained by Equation (2).

$$P(y_{jn}|x_i) = \frac{P(x_i|y_{jn}) \cdot P(y_{jn})}{P(x_i)} \tag{2}$$

For this study, factor analysis, including the number of deficiencies recorded in a single inspection, inspection type, RO performance, gross tonnage, ship age, and SRP, was conducted. By utilizing the Bayesian inference as shown in Equations (1) and (2), the probability of a ship having various deficiencies could be acquired. Furthermore, by virtue of the posterior probability mechanism, the critical factors leading to these deficiencies and detention could be identified. As a result, the characteristics of high risk ships were able to be appreciated. In addition, this study could perform real time inferences for a specific ship according to the ship particulars, inspection type, RO performance, and SRP to predict the ship's probabilities of encountering a deficiency and detention.

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3.3 Model Validation

The following two axioms were used to validate the proposed Bayesian model:

Axiom I: When the state of a parent node parameter slightly increases or decreases, the child nodes must correspondingly increase or decrease.

Axiom II: When the states of multiple parent nodes (whose states have a homogeneous trend) simultaneously increase or decrease, the magnitude of the corresponding change in the child node should be greater than that of the variation resulting from the state increment or decrement of a single parent node.

In this study, Detention will be used as the child node for validation, and Inspection Type and Number of Deficiencies will be used as the parent nodes. When the two parent nodes slightly increase or decrease, the magnitude and trend of the probability variation in Detention node will be used to validate the model. In Equation (3), $P(x_{i,old})$ denotes the original detention probability whereas $P(x_{i,new})$ expresses the new detention likelihood given the state alteration of the parent nodes. $V(x_i)$ is the absolute value of the difference between these two and will be adopted as the reference for the model validation.

$$V(x_i) = \left|P\left(x_{i,new}\right) - P\left(x_{i,old}\right)\right| \tag{3}$$

4 RESULTS AND DISCUSSION

4.1 PSC BN Models for RORO Cargo and Passenger Ships

From the ship data collected concerning deficiencies recorded under the Tokyo MOU PSC, this study extracted eight items to construct the BN model, namely, Defective Item, Detention, Number of Deficiencies, Inspection Type, Performance of RO, Gross Tonnage (GT), Ship Age, and SRP. The model was constructed by taking into account the relevant literature (Dinis et al., 2020; Fan, Zhang, et al., 2019; Jiang et al., 2023; Wang et al., 2021) and the recommendations from the experts and scholars to establish a causal relationship, as shown in Figure 1. A model constructed in this manner can be more closely aligned with practical application.

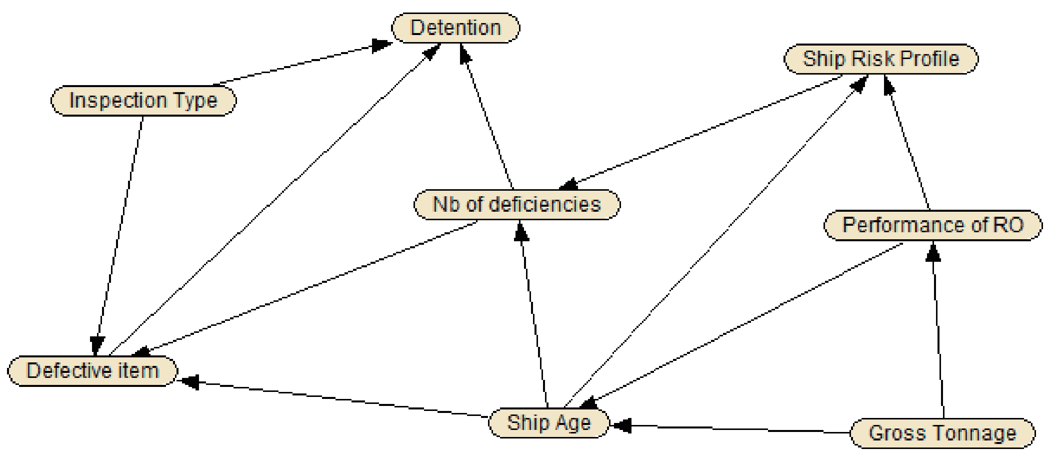

Figure 1. BN influence diagram.

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Allowing for the accuracy of the model analysis, the case studies were divided into two categories i.e., RORO cargo and RORO passenger. Two models for these two ship types were accordingly established based on the historical PSC data, as shown in Figure 2 and Figure 3, respectively. In the literature, some structure-learning-based Bayesian models have found that GT influences Ship Age and Performance of RO. Furthermore, the Tokyo MOU criteria for determining the SRP include both Ship Age and Performance of RO. Therefore, the aforementioned two nodes influence the SRP. Older ships tend to have a higher number of deficiencies. Thus, Ship Age affects Number of Deficiencies. In addition, RO performance is related to the number of inspections, recorded deficiencies, and detentions. Therefore, Performance of RO indirectly influences the distribution of Ship Age. Within the SRP, a higher risk level often correlates with a greater number of recorded deficiencies. Accordingly, the SRP affects the Number of Deficiencies recorded on the ship. A higher Number of Deficiencies often leads to a higher likelihood of detention and the quantity of deficiencies logged affects the specific deficiency items recorded. The primary causes of the recorded deficiency items differ with Ship Age, for instance, the proportion of deficiencies recorded under "Propulsion and Auxiliary Machinery" generally increases with Ship Age.

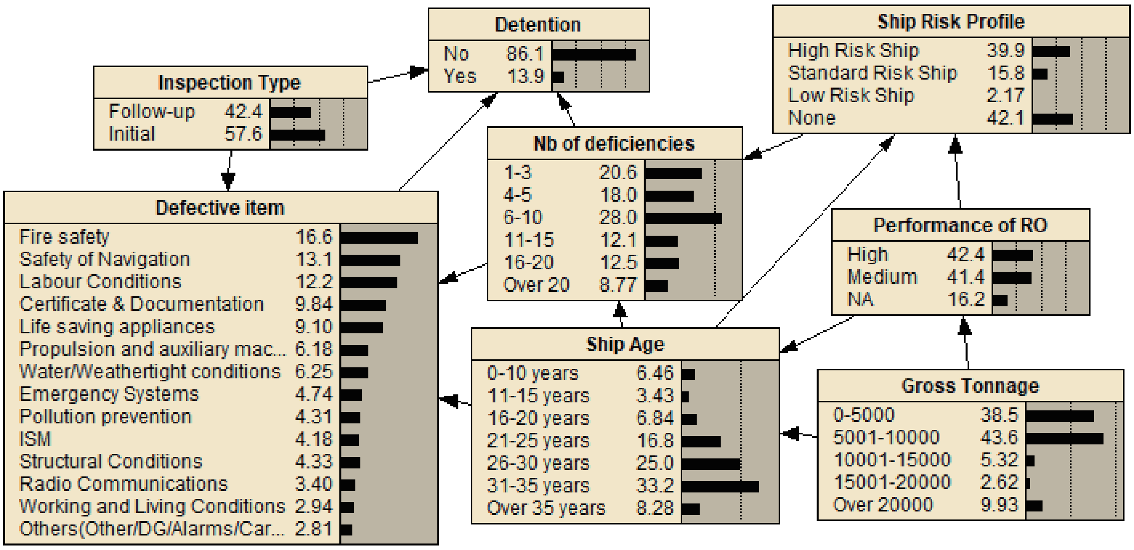

Figure 2. PSC BN model for RORO cargo.

Based on Figure 2, the detention rate for the RORO cargo ships under PSC inspection mechanism is 13.9%. The main deficiency categories include Fire Safety, Safety of Navigation, Labour Conditions, Certificate & Documentation, and Life Saving Appliances. In addition, there were other key findings. Around 65% of the ships under the inspection mechanism have at least one and less than or equal to 10 deficiencies. High Risk Ships (HRS) and ships without a defined Ship Risk Profile (SRP) each account for approximately 40% among the ships. Ships with High or Medium Performance for the RO each account for 40% of the vessels. The majority of the RORO cargo ships with deficiencies are under 10,000 gross tonnage and are between 21 and 35 years of age.

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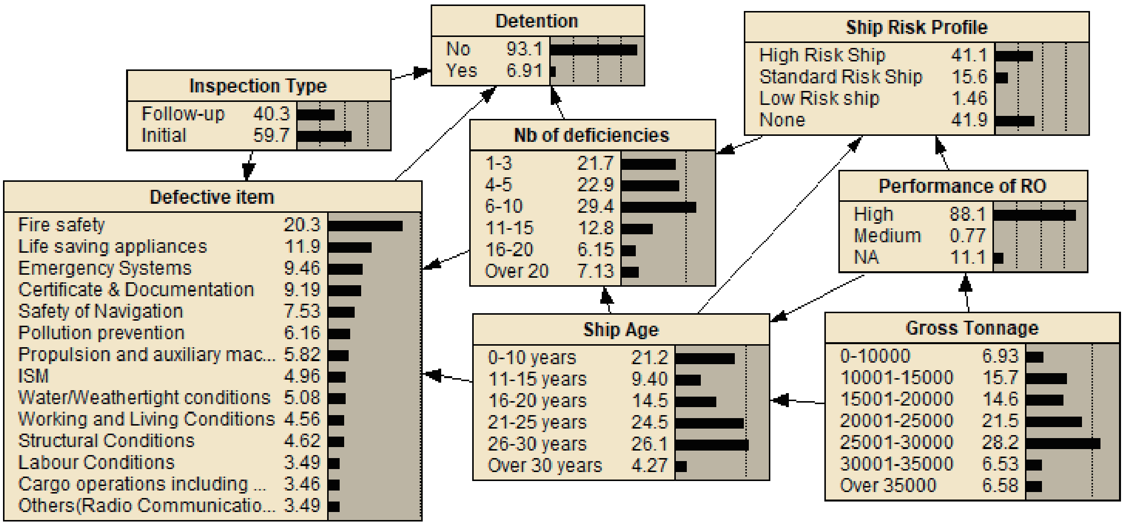

Figure 3. PSC BN model for RORO passenger.

It can be seen from Figure 3 that the detention rate for RORO passenger ships is significantly lower than that of RORO cargo ones, declining from13.9% to 6.91%. The main deficiency categories recorded are also different, mainly including Fire Safety, Life Saving Appliances, Emergency Systems, and Certificate & Documentation. Other key findings are as follows. Around 67% of the ships under the inspection mechanism have at least one and less than or equal to 10 deficiencies. The SRP distribution is similar to that of RORO cargo ships, where ships with HRS and vessels with undefined SRP each account for 40%. The distribution of RO Performance is significantly different from RORO cargo ships, and nearly 90% of RORO passenger ships demonstrate High Performance. The majority of ship gross tonnage is primarily between 20,001 and 30,000, accounting for about 50%. This is followed by 10,001 to 20,000, consisting of around 30%. Ships aged 21 to 30 years account for 50% of the total, whereas those aged 0 to 10 years represent 20%.

A comparison between RORO cargo and RORO passenger ships reveals that the fleet age of RORO cargo is older than that of RORO passenger. In addition, RORO cargo ships have a higher detention rate, a greater number of ships recorded with 10 or more deficiencies, and a larger proportion of ROs showing Medium Performance.

The high-proportion deficiencies recorded for RORO passenger ships are highly related to human safety, including Fire Safety, Life Saving Appliances, and Emergency Systems. On the other hand, for RORO cargo ships, apart from human safety, a greater emphasis has been laid on Safety of Navigation and Labour Conditions in their recorded deficiencies.

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4.2 Model Validation

In order to validate whether the model conforms to Axiom I, Scenarios 1, 2, and 3 were established, which represent the situation where the state probability of the parent node i.e., follow-up inspection, gradually increases. Scenarios 4, 5, and 6 illustrate the situation where the state probability of Follow-up Inspection steadily decreases. Table 3 contains the state magnitudes of Detention of the Original and Scenarios 1, 2, 3, 4, 5, and 6 resulting from the probability alterations. It also shows the variation of each scenario based on Equation (3). It can be seen from the Table that the greater the magnitude of increase or decrease in the parent node, the greater the corresponding change in the child node. Therefore, it can be concluded that the BN model satisfies Axiom I.

Table 3. Variation magnitude of the child node (Detention) due to alteration of a parent node (Inspection Type).

Node		Original	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Inspection Type	Follow-up	0.4244	0.5	0.8	1	0.3	0.2	0
	Initial	0.5756	0.5	0.2	0	0.7	0.8	1
Detention	No	0.86096	0.87466	0.92905	0.9653	0.83841	0.82028	0.78402
	Yes	0.13904	0.12534	0.070954	0.034699	0.16159	0.17972	0.21598
	Variation	**0**	**0.0137**	**0.068086**	**0.104341**	**0.02255**	**0.04068**	**0.07694**

The validation of Axiom II starts from the establishment of Scenarios A, B, and C as shown in Table 4. The first two scenarios represent the case of a single parent node alteration while Scenario 3 illustrates the instance of the multiple parent node adjustment. By comparing the three scenarios and calculating the variation magnitude using Equation (3), it is found that the deviation mass due to the multi-parent node alteration in Scenario C is greater than that of the single-parent node changes in Scenarios A and B. Accordingly, the BN model conforms to Axiom II.

Table 4. Variation magnitude of the child node (Detention) due to alteration of a parent node (Inspection Type & Nb of Deficiencies).

Node		Original	Scenario A	Scenario B	Scenario C
Inspection Type	Follow-up	0.4244	0.4244	1	1
	Initial	0.5756	0.5756	0	0
Nb of Deficiencies	1-3	0.20619	0	0.20619	0
	4-5	0.17995	0	0.17995	0
	6-10	0.2797	1	0.2797	1
	11-15	0.12096	0	0.12096	0
	16-20	0.12549	0	0.12549	0
	Over 20	0.087702	0	0.087702	0
Detention	No	0.86096	0.88465	0.9653	0.9817
	Yes	0.13904	0.11535	0.034699	0.018301
	Variation	**0**	**0.02369**	**0.104341**	**0.120739**

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4.3 PSC BN Model Inference

A Bayesian model can be used for causal inference by specifying ship characteristics to derive the most likely deficiency number and items to be recorded as well as the detention probability. Taking a practical case in Figure 4 as an example, the vessel STENA EGERIA (IMO number: 9243447), with a gross tonnage of 24,418 and 17 years of age at its initial inspection, is most likely to be recorded with 6-10 deficiencies. The defective items most likely to be noted are Fire Safety, Certificate & Documentation, and Life Saving Appliances. Its detention rate is predicted to be 10.1% and this type of vessel is most likely to be categorized as High Risk under the SRP. The vessel was actually first inspected on March 30, 2017. Seven deficiencies were recorded, including two Fire Safety, two Certificate & Documentation, two Life Saving Appliances, and one Water/Weathertight Conditions. The vessel was indeed noted as a High Risk Ship in the inspection record.

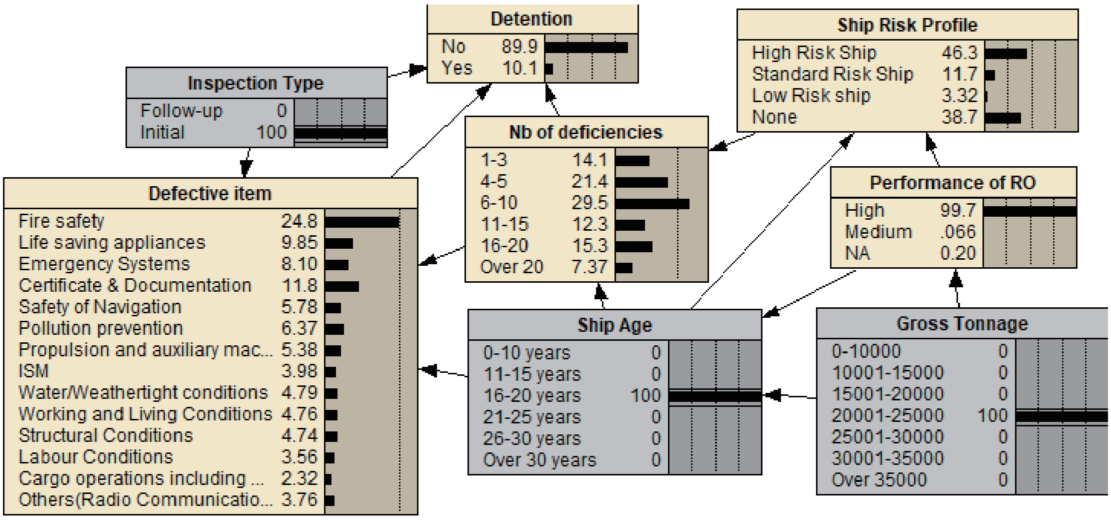

Figure 4. RORO passenger BN inference.

BN models have the capability of conducting reverse inferences from the Detention node to appreciate the most likely characteristics of a detained vessel. Figure 5 illustrates the characteristics of the detained RORO cargo ships. Such vessels are often detained during their initial inspection and frequently have 16-20 deficiencies recorded simultaneously. The most common grounds for detention are Fire Safety, Safety of Navigation, Certificate & Documentation, Labour Conditions, and Life Saving Appliances. A detained RORO cargo ship is most likely a vessel aged 31-35, with a gross tonnage of 5,001–10,000, and whose RO performance is mostly medium.

As a real case example, the vessel SUN RIO (IMO number: 9030644) was recorded with 26 deficiencies during its initial inspection on April 11, 2022. It was detained due to the deficiencies including one ISM, one Pollution Prevention, two Fire Safety, three Safety of Navigation, four Certificate & Documentation, and one Life Saving Appliances. At the time of inspection, the vessel was 31 years old with a gross tonnage of 7,580 and was classified as a High Risk Ship.

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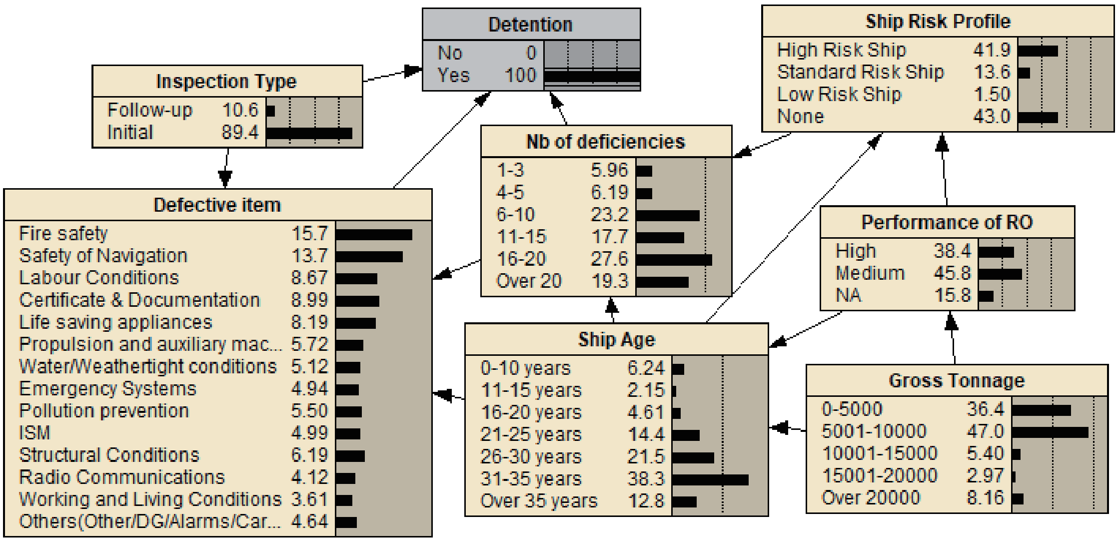

Figure 5. RORO cargo BN inference.

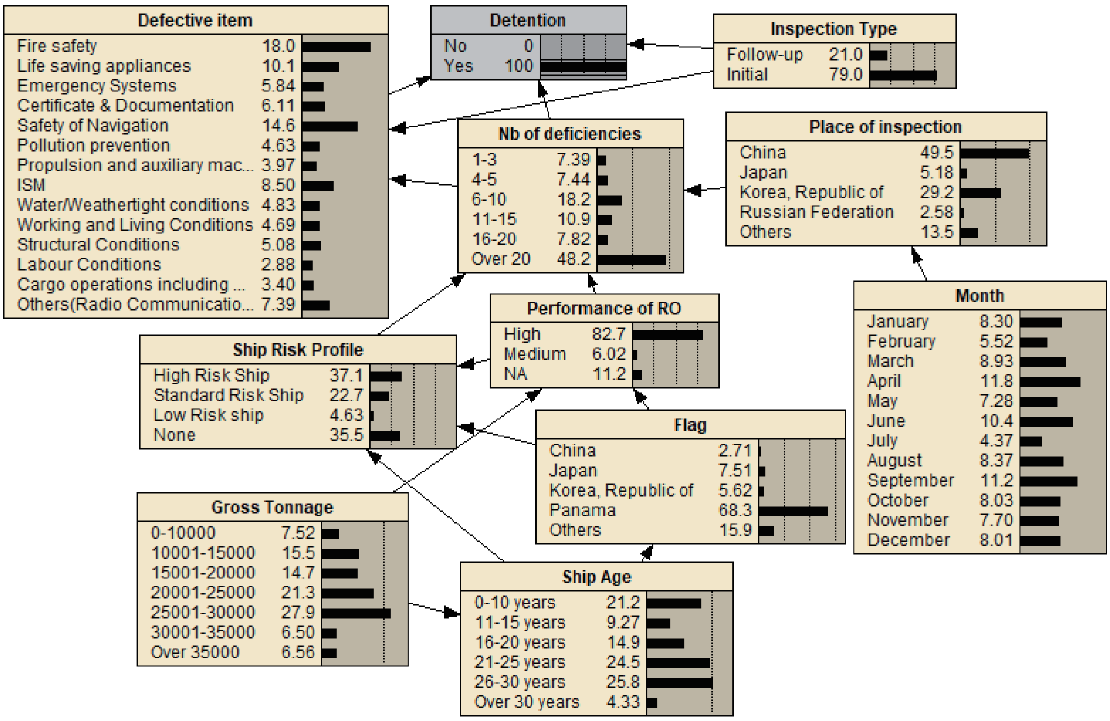

Figure 6. RORO passenger BN inference.

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By virtue of the BN mechanism, the model performs both forward and reverse inference on the various nodes for both RORO cargo and RORO passenger vessels, and it was found that both ship types are typically detained during their initial inspection. During follow-up inspections, the probability of RORO cargo and RORO passenger vessels to be cited for ISM code and Certificate & Documentation deficiencies shows a significant increase.

When the probability of detention is set to 100%, the Bayesian inferences for RORO cargo and RORO passenger ships shown in Figure 5 and Figure 6 reveal the following:

- The characteristics of RORO cargo vessels most likely to be detained are: 5,001–10,000 gross tonnage, 31–35 years of age, Medium Performance of RO, Undefined SRP, and 16–20 recorded deficiencies. The deficiencies most likely to be recorded include Fire Safety, Safety of Navigation, Labour Conditions, Certificate & Documentation, and Life Saving Appliances.
- The characteristics of RORO passenger vessels most likely to be detained are: 25,001–30,000 gross tonnage, 26–30 years of age, and High Performance of RO with a High Risk Ship profile and more than 20 recorded deficiencies. The deficiencies most likely to be logged include Fire Safety, Safety of Navigation, Life Saving Appliances, ISM, and Others.

By virtue of the aforementioned pattern, other findings are derived[1]. Under conditions where only Deficiency items are considered while the other nodes remain constant:

- For RORO cargo vessels, when Structural Conditions or Others deficiencies are recorded, the detention rate increases to approximately 20%.
- For RORO passenger vessels, when ISM, Safety of Navigation or Others deficiencies are found, the detention rate rises to over 10%.

Under conditions only ship age is considered while the other nodes remain constant:

- RORO cargo vessels with an age between 31–35 years or over 35 years show a significant increase in detention rate. When the age is over 35 years, the detention rate rises to 21.4%, which is highest amongst the other age groups. There is an approximately 45% probability of 16 or more deficiencies to be found. The vessel is most likely a 5,001–10,000 GT ship with Medium RO performance. The deficiencies most likely to be recorded are Safety of Navigation, Fire safety, Certificate & Documentation, and Labour Conditions, with a significant increase in the probability of Structural Conditions.

Under conditions where only ship age is considered while the other nodes remain constant:

- RORO passenger vessels over 30 years of age show a detention rate increase to 18%, which is higher than other age groups. There is an approximately 28.7% probability of over 20 deficiencies to be found. The vessel is most likely a 0–15,000 GT ship with High or NA RO performance. The deficiencies most likely to be logged are Working and Living Conditions, Fire safety, and Certificate & Documentation, with a significant increase in the probability of Working and Living Conditions, ISM, and Others.

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[1]Due to space constraints, the BN inference figures are omitted here but are available from the authors upon request.

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5 CONCLUSION

Detention rate for RORO cargo ships ranks the second highest among all vessel types in the Asia-Pacific region; however, few PSC studies specifically target RORO ship inspections. Furthermore, RORO passenger ships account for half of all marine casualty incidents in European waters involving passenger vessels. Thus, this study developed a BN model to analyze the PSC framework for RORO ships. The objective is to strengthen the effectiveness of PSC inspections for RORO vessels and provide valuable references for both maritime authorities and shipowners.

According to the Tokyo MOU from 2015 to 2024, a total of 5,917 deficiencies were recorded for RORO cargo ships, whereas 4,783 were cited for RORO passenger ships. RORO cargo ships have a higher average vessel age, higher detention rates, and a greater number of vessels with 10 or more deficiencies. In addition, a larger proportion of RORO cargo ships was associated with "Medium" Performance of RO. The most frequent deficiencies for both ship types include Fire Safety and Certificates & Documentation. However, RORO passenger ships are also frequently cited for deficiencies in Life Saving Appliances and Emergency Systems, indicating a high correlation with safety of life. In contrast, in addition to human safety, the PSC inspections for RORO cargo vessels place a significant emphasis on navigational safety and labour conditions. The most common deficiencies include Safety of Navigation, Labour Conditions, and Life Saving Appliances.

Inferences from the BN model indicate that when RORO ships are detained, it most frequently takes place during the initial inspection. However, the probability of being cited for ISM and Certificate & Documentation deficiencies increases significantly during the follow-up inspections. Based on the BN inference, profiles of the RORO ships most susceptible to detention are identified as follows. RORO cargo ships with a capacity of 5,001–10,000 GT, age of 31–35 years, Medium Performance of RO, undefined SRP, and 16–20 recorded deficiencies are prone to encounter such an intervention action. RORO passenger vessels, on the other hand, with a ship size of 25,001–30,000 GT, age of 26–30 years, High Performance of RO, High Risk Ship profile, and more than 20 recorded deficiencies are likely to face the PSC countermeasure.

The detention rates for RORO cargo ships increase notably when deficiencies are cited under Structural Conditions or Others. Similarly, for RORO passenger ones, detention rates rise dramatically when deficiencies related to ISM, Safety of Navigation or Others are recorded. When considering ship age as the sole variable (without specifying the states for other nodes), the age group of over 30 years significantly elevates the detention risk for all RORO vessels. Specifically, for RORO cargo ships over 35 years old, the detention rate rises to 21.4%, accompanied by a remarkable increase in the probability of Structural Conditions deficiencies. Likewise, for RORO passenger ships over 30 years old, the detention rate escalates to 18%, with a significantly higher likelihood of deficiencies in Working and Living Conditions, ISM, and Others.

The findings generated could be deemed as contributions for the maritime industry. These include the understanding of RORO PSC performance and the characteristics of RORO cargo and passenger ships likely to encounter detentions. Notable deficiency types and age group triggering higher detention rates are also appreciated. The aforementioned outcomes could be the useful references for government agencies, shipowners, insurance companies, and other stakeholders in the shipping industry. Due to the strength of forward and backward analysis, BN inference may be applicable to other subjects in the maritime domain including marine casualty analysis, merchant ship safety analysis, and fishing vessels study. However, such an inference is only able to provide reliable findings given the availability of abundant data. The more information accessible for analysis, the higher the degree of validity of the research outcomes. Given the data availability, nevertheless, the proposed framework could be applied to marine casualty analysis, navigation risk analysis, ship selection mechanism for vessel traffic services, and PSC inspections.

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